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Seismic Performance of Two Story Steel Building Using Shape Memory Alloys (SMAs) Bars

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Abstract

Shape Memory Alloys (SMA) is type of smart materials that have ability to undergo large deformation and return back to their undeformed shape through heating (shape memory effect) or removal of load (superelastic effect). This unique ability is useful to enhance behavior of structure and seismic resistance. In this paper, superelasticity (SE) effect of NiTi alloys is used to improve the structural characteristics of steel building. The finite element analysis of steel building is done using ABAQUS v.2017. In order to compare the structural behavior of the steel building equipped with Shape Memory Alloy bars at beam-column connection, three steel building was modeled with a different combination of high strength steel bars and SMA bars. The steel building was checked for time history analysis by using Vrancea 1977 earthquake data. In order to estimate the recentring ability, residual of roof displacement and energy dissipation. The steel building equipped with SMA bars shows 82.7%, 152.72% recovery in residual roof displacement for steel building equipped with 50 % SMA bars and 50% HS steel bars and steel building equipped with 100% SMA bars respectively, and moderate energy dissipation. In general, the frame equipped with 50% superelastic SMA bars and 50% HS steel bars provided better seismic performance.

Keywords: Beam-Column Connection, Smart Materials, Shape Memory Alloys, Bars, Recentering Ability.

1. Introduction

High residual deformations and brittle fracture of conventional moment resisting frame that incorporating welded beam-column connection after earthquake action, thus a new system of structural steel which was the ability of recentring and energy dissipation is required in order to address such problems. Lately, the application of smart material (shape memory alloys SMA), particularly with nickel-titanium (NiTi) has attracted a lot of attention in the society of researchers of civil engineering. SMAs are a type of alloys that show a unique feature to undergo large deformations and return back to undeformed shape through either heating known as the shape memory effect (SME), or by removing the load that causes the deformations known as the superelastic effect (SE). Owing to these extraordinary properties, SMA materials have already been effectively used in projects of civil engineering [1].

Dolce et al. suggested and tested the three types of (SMA) Nitinol wire-based devices: supplemental recentering device (SRCD), recentering device (RCD), non recentering device (NRD), the use of SMA and SRDC isolation devices in structure [2]. Ocel et al. perform the H shaped beam to H shaped column connections by using SMA bars as moment transferred element with diameter 35 mm. upon heating the SMAs bars above the transformation temperature, results showed stable and repeatable hysteretic behavior [3]. Penar study the behavior of beam-column connection with SMA tendons in the austenite phase. The tendons with a diameter of 19.05 mm. the tendon was machined into a shape of a

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dog bone with a reduced section diameter of 12.7 mm. Results displayed better recentering ability than reference connection with steel tendons [4]. Fang et al. conducted eight extended endplate connections which included one traditional connection with HS steel bolts and seven connections equipped with SMAs bolts. The SMA specimens of connection presented excellent recentering ability and moderate energy dissipation, while the traditional connection with HS steel bolts exhibited good energy dissipation but with a considerable amount of residual deformation [5]. Sultana and Youssef conducted the seismic performance of ten story frames with shape memory connection at a certain location to investigate the inter-story drift, maximum residual inter-story drift and damage schemes. This study shows that replacing all rigid connection by SMA connection significantly increased the inter-story drift and reduced the maximum residual inter-story drift [6].

Wang et al. performed an experimental investigation for eight specimens of using combined superelastic SMA bolts and steel angles. The main parameter included SMA bolts pre-strain, bolt length, angle thickness, and layout of bolts and angles. All specimens exhibited desired deformation modes also showed a moderate amount of energy dissipation. In addition, the stiffness of specimens started to decrease evidently because of the SMA bolts relaxation [7]. Ahmad and Shahria conducted finite element analysis to evaluate the cyclic behavior of post-tensioned steel connection with angles made of SMA material [8]. It was found that although no plastic strain remained in the SMA angles after cyclic loading, the dissipated energy was not as good as the steel angles. Fang et al. performed an experimental and numerical investigation on the influence of composite slab systems on the cyclic performance of self-centering connection equipped with superelastic SMA bolts. The specimens exhibited typical flag shape hysteretic curves with expected deformation modes and good self-centering ability, also the specimens show good ductility with no bolt fracture and a moderate amount of energy dissipation [9]. Bajoria and Jadhav performed numerical analysis of using two types of shape memory alloys (SMAs) plates at hinge locations of steel frame subjected to seismic loads. The performance of two superelastic SMAs material plates (NiTi and ferrous) are compared with steel plate, they found when used NiTi and ferrous at connection in form of extended endplate the recovery in residual deflection is almost 99%, 90% for NiTi and ferrous respectively, as compared with steel plate [10].

Elsawy et al. investigated numerically The effect of changing the reverse phase transformation and final stress value of the reverse phase transformation for SMA bolts on the flexural behavior of beam-column connections they found the decreasing values of Starting stress value for the reverse phase and Final stress value for the reverse phase transformation rather than Starting stress value for the forward phase transformation and Final stress value for the forward phase transformation, respectively, increases net area under loading and unloading hysteresis curves and so, the more energy dissipation, the better characteristics in the behavior of such connections within dynamic effects [11]. Sultana and Youssef studied the seismic performance of modular steel braced frames using finite element. The connection utilized either high strength steel bolts or superelastic shape memory alloys bolts. They confirmed that using SMAs bolts can reduce the residual drift, thus improving the seismic performance of the frame as compared with steel counterparts [12]. Elbahy et al. studied the seismic performance for six-story of reinforced concrete frame retrofitted using external superelastic SMA bars and compared to the behavior of regular steel reinforced concrete frame. They confirmed that using superelastic SMA bars can only reduce the maximum drift and residual drift of the frame. In addition, it is more economical to retrofit the steel RC frame using external SMA bars on the first floor [13]. Chowdhury et al. presented a numerical simulation of cyclic behavior of post-tensioned beam-column connections with SMA strands to evaluate the effect of length on the connections. The results of this study show that the shorter length SMA strands are effective in regaining self-centering and dissipate the higher amount of energy compared to the steel strands [14]. Bajoria KM et al. conducted a numerical analysis of three-story frame. Three-moment resisting steel frames with steel, NiTi and Fe based SMA alloys endplates which were located between beam-column connection were performed using ANSYS 15 software. the frame equipped with SMA is able to recover about 90% of residual displacement after incremental lateral loading-unloading cycle [15]. Xu et al. carried out an experimental and numerical analysis on the self-centering link beam using post-tensioned steel-SMA composite tendons. The results showed that the self-centering link beam system using composite tendons was able to re-center from the designed rotation of 8% rad with negligible residual deformations and a moderate amount of energy dissipation [16].

The high energy dissipation and ductility in conventional beam-column connection is often associated with local buckling of beams, this plastic local buckling deformation is very costly to repair after earthquake action, thus in these type of connections the high strength steel bolts were replaced by superelastic SMAs bars which the deformation of superelastic SMAs bars could be accommodated of the energy dissipation and ductility demands. Such that the superelastic hinge could be formed within the connections while the structural parts (endplate, beam, column) are mainly within elastic range and thus can be minimized the damage and cost for repair after earthquake shake. Therefore the novel advantage of these design concepts is to minimize the post-earthquake repair. Feasibility of these types of connections was studied by a number of researchers, these studies focused on the behavior of beam-column connection but without further information about the behavior of steel building under earthquake loads. Thus this research aims to evaluate the replacement ratio superelastic SMAs bars of high strength steel bars and obtain the optimum performance of steel building under seismic loading.

2. Shape Memory Alloys (SMAs)

SMAs (Ni-Ti) are class an extraordinary of metal that displays several unique properties such as the ability to recover large deformation with little permanent of the residual strain, through either heating (shape memory effect) or unloading (superelasticity effect). superelastic Nitinol (nickel-titanium naval ordnance laboratory) is a type of SMA with a unique ability to sustain large strain as high as (6-8%), HS, large fatigue resistance, and high damping, these properties the superelasticity make them desirable for passive vibration control systems. during deformation, SMA will undergo to phase transformation (solid to solid) between its stable two phases namely austenite and martensite. typically martensite is stable at high stress, whereas austenite is stable at low-stress values, when It is loaded the Nitinol transforms from austenite to martensite, upon unloading the martensite transform back to its original parent or austenite phase, Using superelastic Nitinol bars in steel beam-column connection as moment transfer elements will create smart structure that spontaneously adjusts to seismic action, the recovery shape is shown in Figure 1 [18].

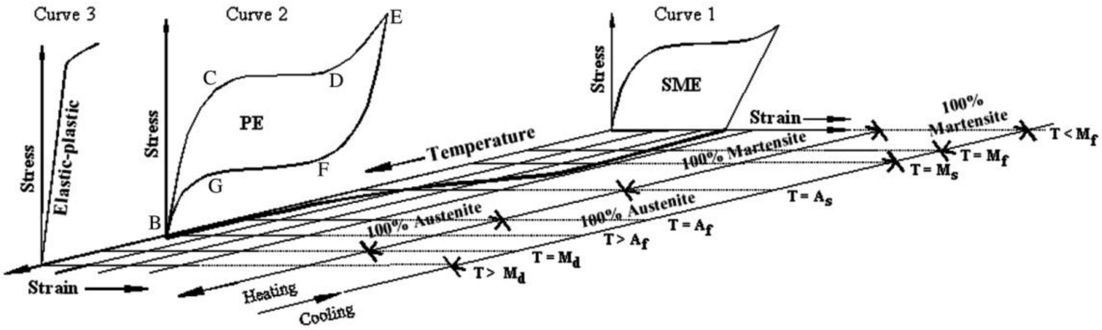


Figure 1. Stress-strain-temperature relationships in SMA [18]

3. Finite Element Modeling and Validation

3D finite element models are generated, that are meshed, and analyzed using finite element software, ABAQUS [19] The finite element model was subdivided into several independent parts such as beam, hollow steel column, SMA bars, HS steel bars, endplate, stiffener. These parts were modelled as half symmetric models using symmetric boundary condition option in order to minimize the computational effort. The models analyzed depend on three-dimensional quadratic tetrahedron element (10-node tetrahedron, (C3D10M)). The details of the case study described below.

3.1. Case Study

One bay two story steel building consists of 8800 mm of span and 3800 mm story height for two floors as shown in Figure 5. The supports are considered fixed supports. The endplate connection consists of a hollow steel section HSS column of 16×16×500 and a beam of W24×103, and an endplate composed of a plate 977.9×381×25.4 mm which welded to beam by 7.9375 mm fillet welding, the design demanded the use of stiffener plates that welded between the endplate and the beam flange. Sixteen 25.4 mm diameter fasteners were run through the HSS column,558.8 mm long bars with one washer at each end which were the superelastic SMA bars located above the upper flange and below the low flange of the beam and the HS steel bars located inside the beam flange. The connection details are taken from finite element model of Hu, 2015 [17]. As shown in Figure 2 and the finite element model shown in Figure 3.

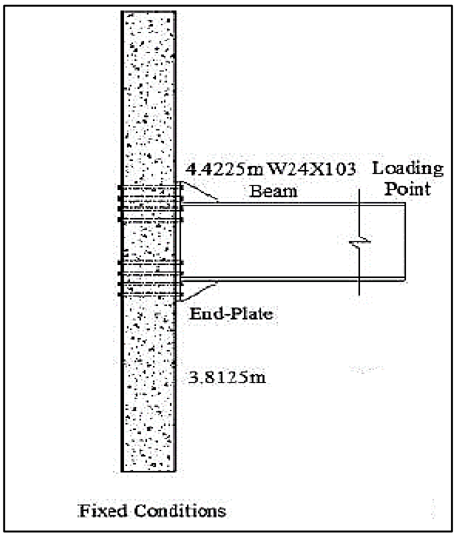


Figure 2. Typical connection configuration [17]

3.1.1. Interface Condition

Finite sliding surface to surface technique method was recommended for all the contact surfaces. The contact properties between the endplate and flange of a column and between underside bolt head and endplate surface surrounding the bolt holes were modelled as a tangential contact using penalty formulation with the friction coefficient is 0.23 and 0.33 respectively. Normal behavior contact properties using penalty formulation were recommended for the normal behavior between the same components. The tangential behavior between bolt shank and the bolt hole was recommended to be frictionless [17].

3.1.2. Materials Properties

The material properties of steel for the component parts were modelled according to A572 Gr 50 steel with the fully nonlinear isotropic properties while the material properties of HS steel bolts and nuts are modelled according to A490 bolt material as shown in Table 1. The superelasticity algorithm available in ABAQUS v.2017 was employed to simulate the superelastic behavior. The mechanical properties for NiTi SMAs are taken from DesRoches et al. [18] as shown in Table 2.

Table 1. Mechanical properties (a) A572-Gr-50 steel, (b) A490 bolt [17]

Parts	True stress (MPa)	True plastic strain	Young modulus (MPa)	Fy (MPa)	Fu (MPa)
(a) ABAQUS input values for A572-Gr-50 steel	379.639	0	199810	378.95	502.97
	458.5295	0.09302			
	617.2751	0.204			
(b) ABAQUS input values for A490 bolt	587.3725	0	199810	585.65	1033
	837.5484	0.00872			
	993.538	0.02459			
	1116.18	0.07137			

Table 2. Mechanical properties of SMA materials. DesRoches et al. [18]

Property	
Poisson's ratio	0.3
Elastic modulus	40000
martensite start stress	440 MPa
martensite finish stress	540 MPa
austenite start stress	250 MPa
austenite finish stress	140 MPa
Transformation strain	0.045
As (°C)	-11 °C

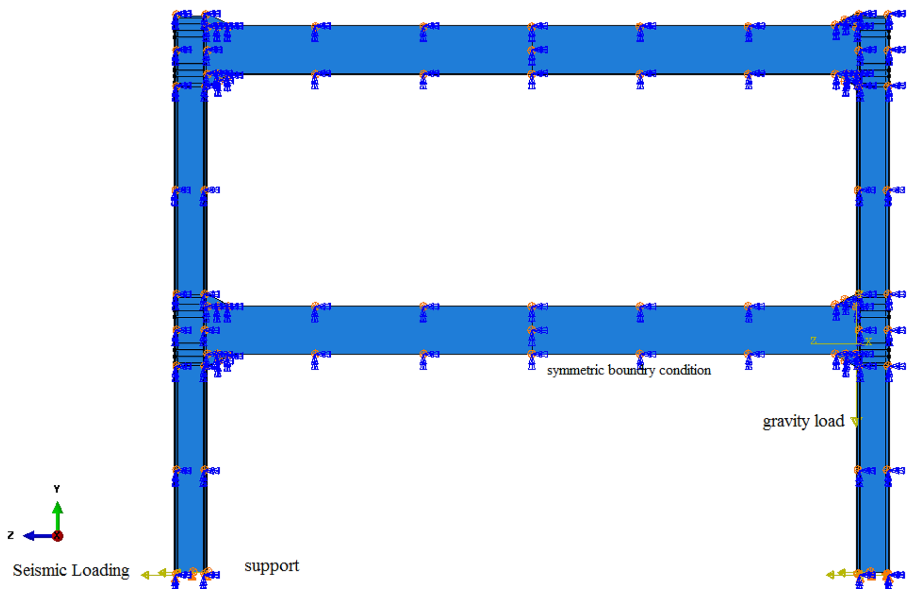
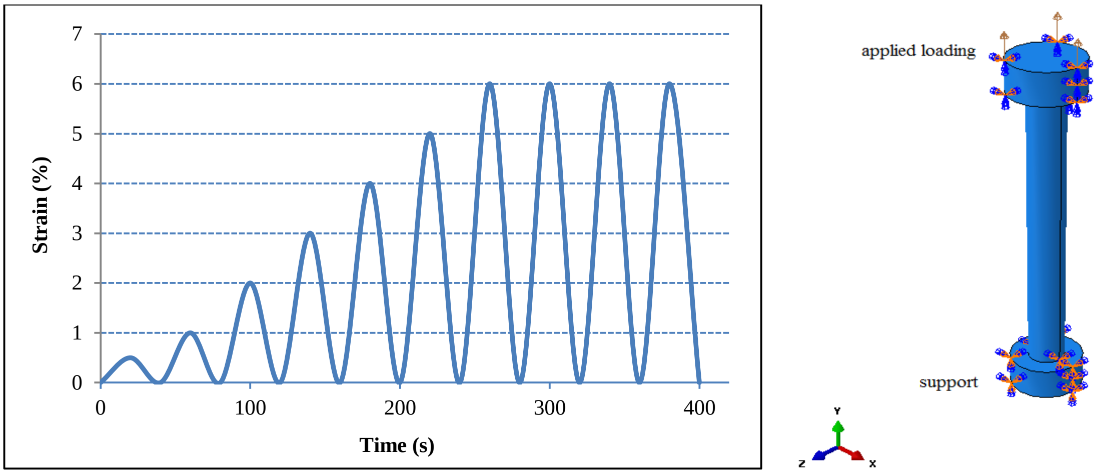


Figure 3. FM model of frame

In order to accurate the procedure of nonlinear finite element simulation the results of finite element analysis were compared with experimental results of DesRoches et al. [18]. The details of the experimental test are defined below.

3.2. Validation (specimen tested by DesRoches et al. [18])

Testing of the 25.4 mm in diameter bar was conducted by using a (2.7 MN) MTS uniaxial servo-controlled hydraulic frame and an INSTRON 8500 plus controller. The loading protocol as shown below was input utilizing an MTS test star controller running Testware program. The loading protocol used, shown in Figure 4(a), consists of increasing strain cycles of 0.50%, 1.0–5% by increments of 1%, followed by four cycles at 6%. And the modeling of test shown in Figure 4(b).



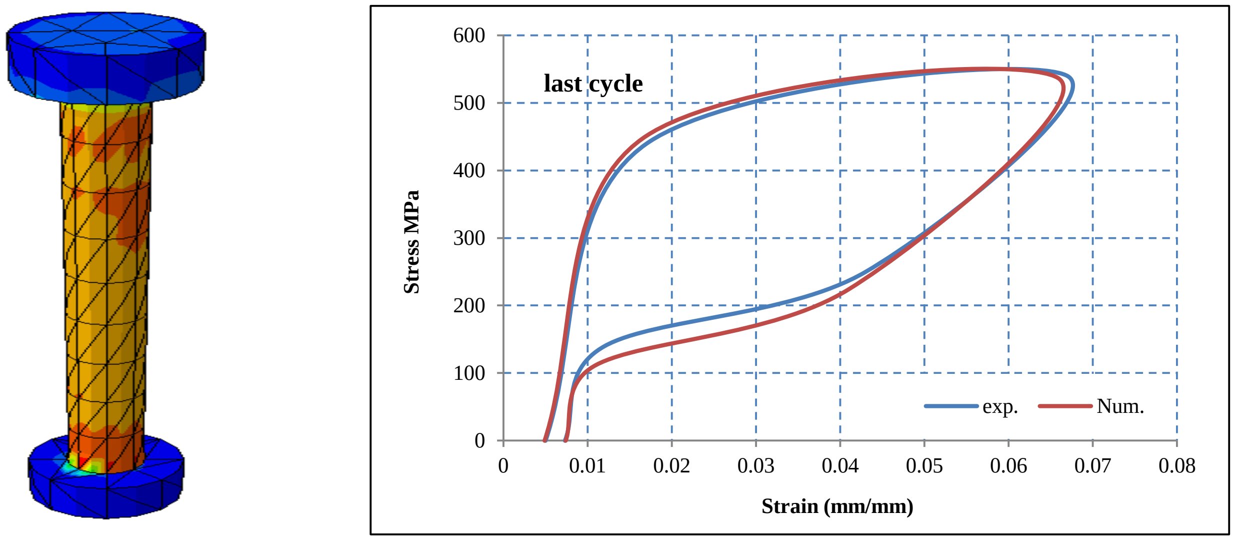
(a) (b)

Figure 4. (a) Loading protocol for the cyclic test of SMA bars, DesRoches et al [18], (b) Applied to load in ABAQUS

The results of the experimental test and numerical simulation show good agreement these results as shown in Figure 5.and in the Table 3.

Table 3. Comparison between experimental and numerical results.

Type of stress	Exp. (MPa)	Num. (MPa)
martensite start stress	440	448
martensite finish stress	540	536
austenite start stress	250	224
austenite finish stress	140	112



(a) (b)

Figure 5. (a) Cyclic tension test of SMA bar in ABAQUS, (b) stress-strain for 25.4 mm SMA bar subjected to quasistatic cyclic loading (Last cycle)

4. Results and Discussion

At the beginning of the analysis, the models were simulated under the effect of free vibration and the six Eigenmodes and frequency for two-story steel building is studied. After that the response of two story steel building for earthquake action is studied by using time history analysis with Vrancea earthquake data 1977 [11], the time period is considered one second as shown in Figure 6.

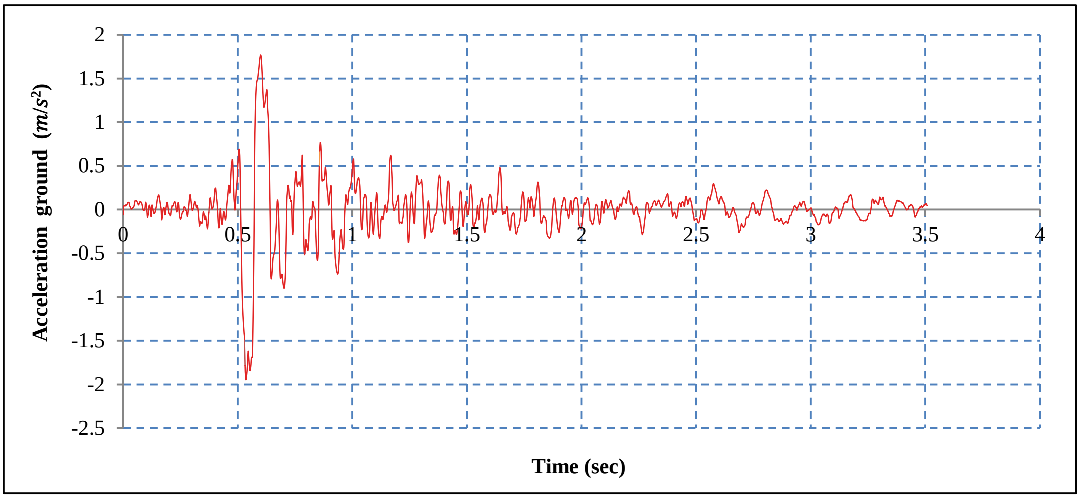


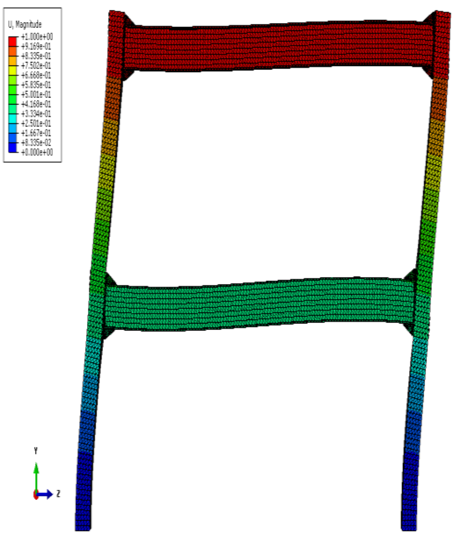
Figure 6. North-south component of Vrancea earthquake in 1977 [20]

4.1. The Response of Two Story Steel Building in Free Vibration Mode

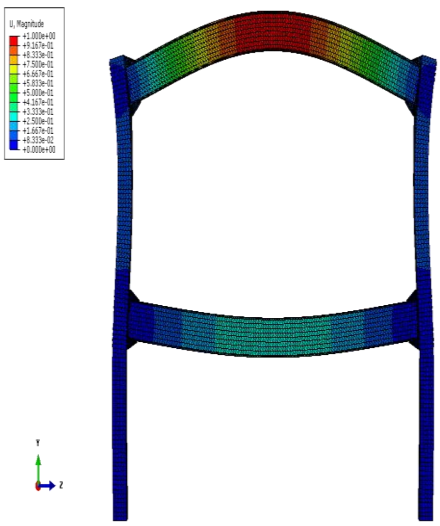
This type of analysis has been implemented in order to get the natural frequency and corresponding mode shapes of the steel building and the distribution the behavior of the system as shown in Table 4 and Figure 7.

Table 4. The natural frequency of analysis results

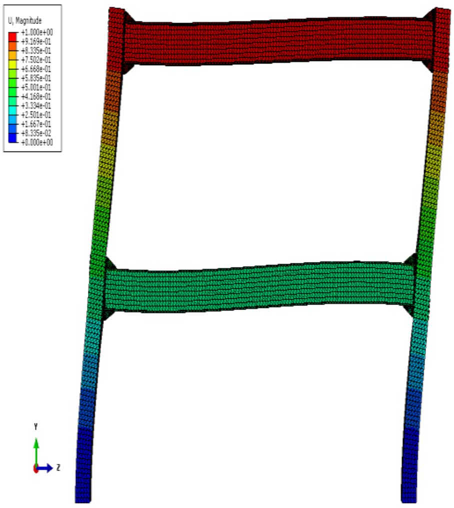
Mode No.	Frame equipped with 100% steel bars. Frequency f(cycle/sec)	Frame equipped with 50% steel bars and 50% SMA bars Frequency f(cycle/sec)	Frame equipped with 100% SMA bars. Frequency f(cycle/sec)	Symmetrical/ Unsymmetrical
1	9.220	9.236	9.157	Unsymmetrical
2	29.199	29.108	29.070	Symmetrical Y axis
3	32.120	32.290	32.048	Unsymmetrical
4	33.400	33.173	33.093	Symmetrical Y axis
5	83.786	83.910	83.781	Unsymmetrical
6	90.734	90.751	90.648	Unsymmetrical



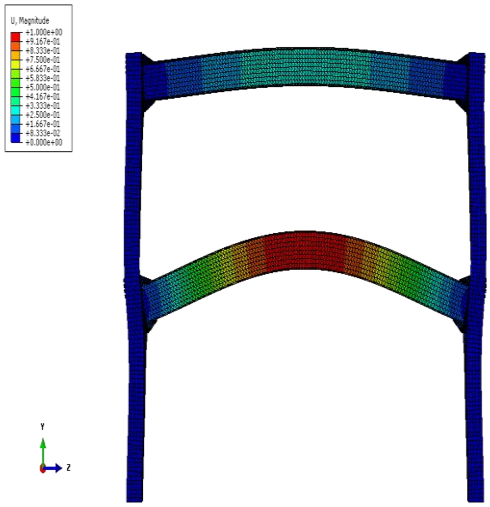
Eigen mode 1



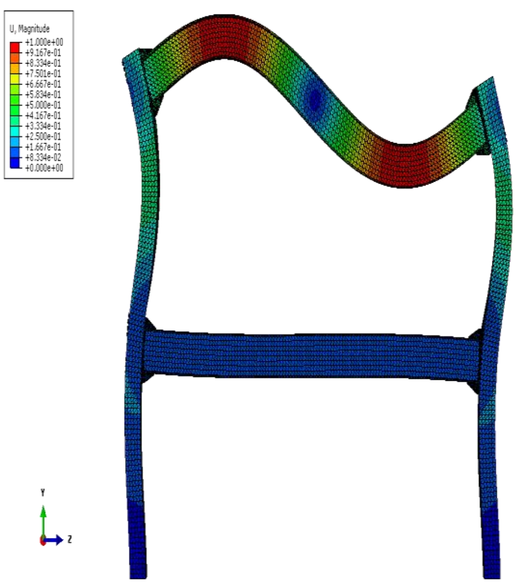
Eigen mode 2



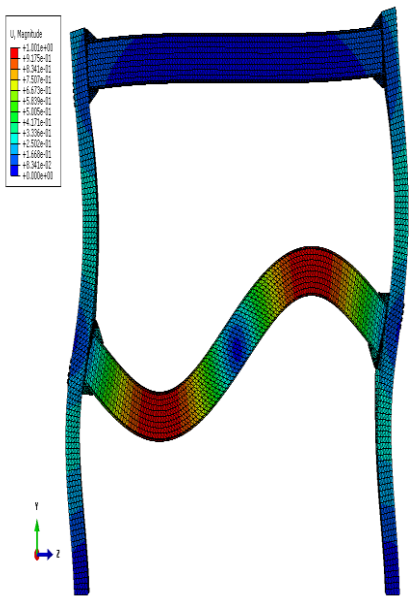
Eigen mode 3



Eigen mode 4



Eigen mode 5



Eigen mode 6

Figure 7. Mode shape of two storey smart steel building

4.2. The Response of Two Story Steel Building under Seismic Loading

The added superelastic SMA bars instead of steel bars is investigated by replace it with replacement ratio 0%, 50%, 100%. And the performance of steel building is estimate by the following parametric study (recentering ability and story drift, roof displacement, energy dissipation, maximum and residual stress in building)

4.2.1. Recentering Ability and Story Drift

The Recentering ability of the superelastic SMA connection refer to the amount of residual rotation in the connection. It can be calculated as the difference between a maximum drift and the residual drift then divided by the maximum drift [21]. The response of two story steel building is studied for earthquake acceleration using time history analysis with Vrancea earthquake data [20]. The time period is considered one second. the storey drift in reference model get decreases by (1.16%, 5.23%) as compared with frame equipped with 50% SMA bars and 50% steel bars and frame equipped with 100% SMA bars respectively. Moreover (93.7%) reduction in residual story drift is seen in case of building equipped with 50% SMA bars and 50% steel bars as compared with the reference model. additionally 209.12% reduction in residual story drift in case of building equipped with 100% SMAs as compared with the reference model as shown in Figure 7 and Table 5 this table present the recentering ability of connection. 136% of the maximum drift was restored in case of frame equipped with 100% SMA bars, The frame equipped with 100% SMA bars appears strong recentering ability of SMA bars, because of the phase transformation below the plastic capacity of the beams, the large deformations likely at low loads and also the little amount of dissipated energy. Most the opposite case can be seen in frame equipped with 100% HS steel bars (reference model), where the large residual deformations, large initial stiffness, and high amount of energy dissipation are appeared. Furthermore combination of SMA bars and HS steel bar (two types of tension bars: where moderate amount of energy dissipation and recentering ability) show 98% of the maximum drift was restored.

Table .5 recentering ability of steel building under time history analysis

Frame model	Residual drift (rad)	Residual drift % compared to reference model	Recentering ability %
Reference model	0.002685	-	-
Frame equipped with 50% SMA bars and 50% steel bars	0.00017	93.7	98%
Frame equipped with 100% SMA bars	-0.00293	209.12	136%

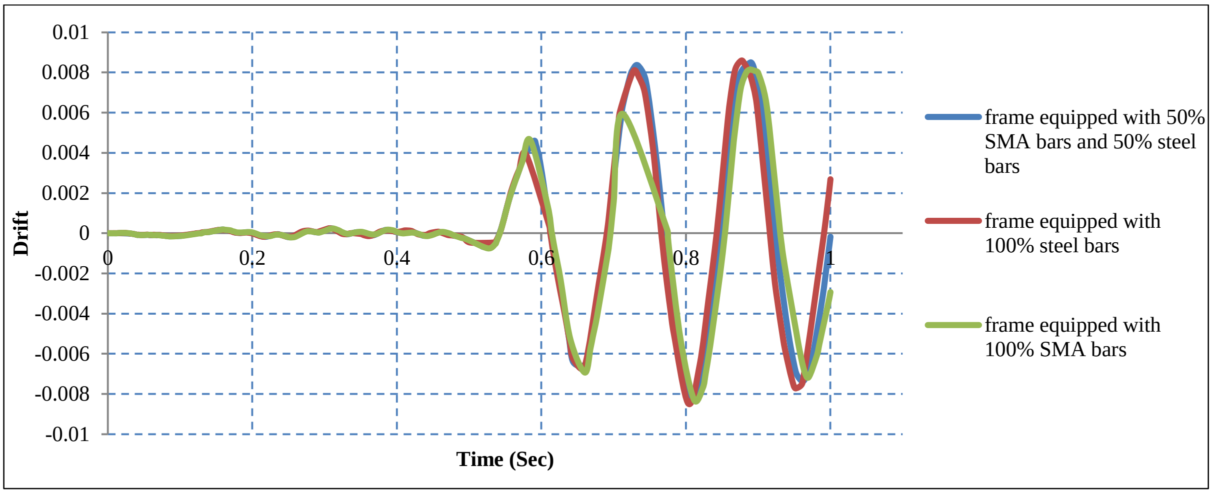
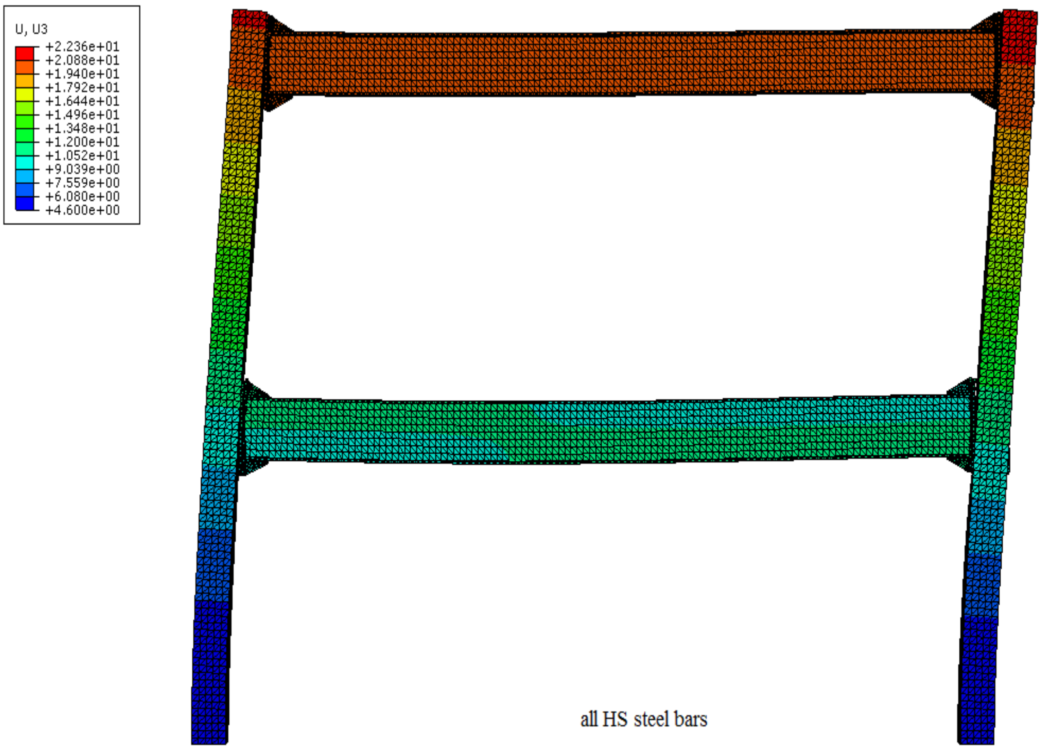


Figure 8. Story drift in the Z direction of the frame with a connection having different materials (time history analysis)



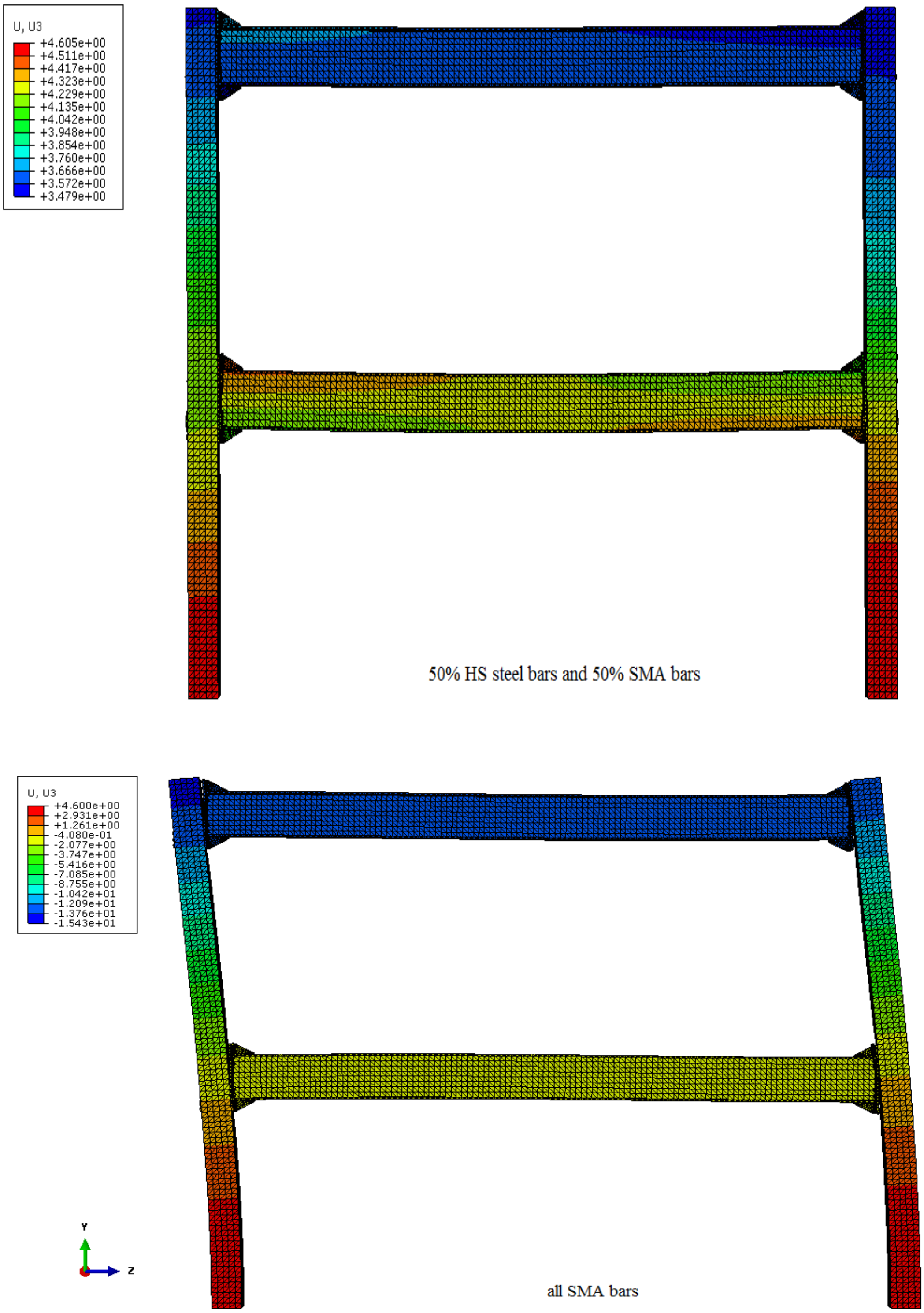


Figure 9. Deflection shape of Story drift in the Z direction (displacement mm)

4.2.2. Roof Displacement

The maximum roof displacement of the reference model (steel building equipped with 100% HS steel bars) under acceleration data is 67.1 mm and the residual roof displacement is 21.67mm. 82.7% reduction (recovery) in residual roof displacement is shown in case of building equipped with 50% NiTi SMA bars and 50% HS steel bars, the maximum roof displacement of two stories under acceleration data is 67.4mm and residual roof displacement is 3.751 mm. While 152.72% reduction (recovery) in residual roof displacement is shown in the case of steel building equipped with 100% SMA bars. The maximum roof displacement, in this case, is 61.4 mm and residual roof displacement is -12.72 mm (the negative sign refers to the opposite direction). As shown in Figure 10 and Table 6. This is because of the SMA bars have the ability to recover deformation or recover elongation up to 8% through removal of the load. Also, the residual strain observed in SMA bars is 0.001339 mm/mm, while in HS steel bars is 0.001648 mm/mm.

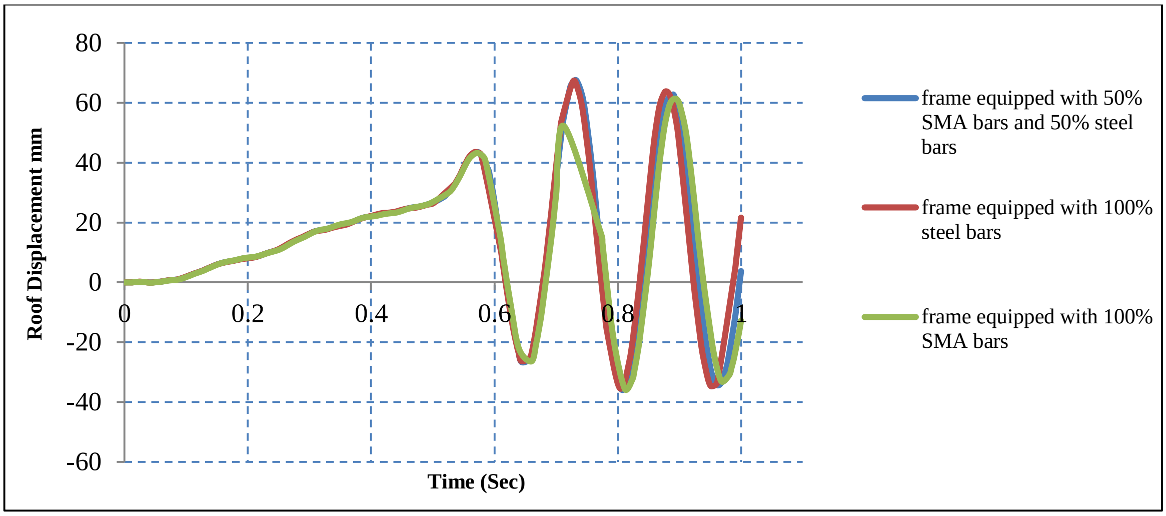


Figure 10. Residual displacement under time history analysis.

Table 6. Comparative performance of frame of time history analysis

Frame model	Residual Displacement (mm)	The decrease in residual displacement compared to the reference model (%)	Max. Displacement (mm)
Reference model	21.67	-	67.1
Frame equipped with 50% steel bars and 50% SMA bars	3.751	82.70%	67.4
Frame equipped with 100% SMA bars.	-12.72	158.72%	61.4

4.2.3. Energy Dissipation

The energy dissipation ability of frame equipped with SMA bars and steel bars is examined here via plastic dissipated energy per unit volume "PENER" (energy dissipation by rate independent and rate dependent plasticity per unit volume [19]. As a function of energy dissipation. Which is defined as: $\int_0^t \sigma_p : \varepsilon_p^{pl} dt$. Where σ_p and ε_p^{pl} represents the stress and plastic strain components. [19]

Figure 11 present the effect of added superelastic SMA bars instead of steel bars on energy dissipation. The energy dissipation related to the stress and strain (energy dissipation is recorded as the integration of the stress versus strain hysteresis). The steel building equipped with 100% HS steel bars can be dissipated (32%, 36.5%) large energy compared to that of steel building equipped with 50% SMA bars and 50% HS steel bars and steel building equipped with 100% SMA bars. This is because the large the hysteretic loop of structural steel compared to flag shaped hysteresis of the superelastic SMA materials.

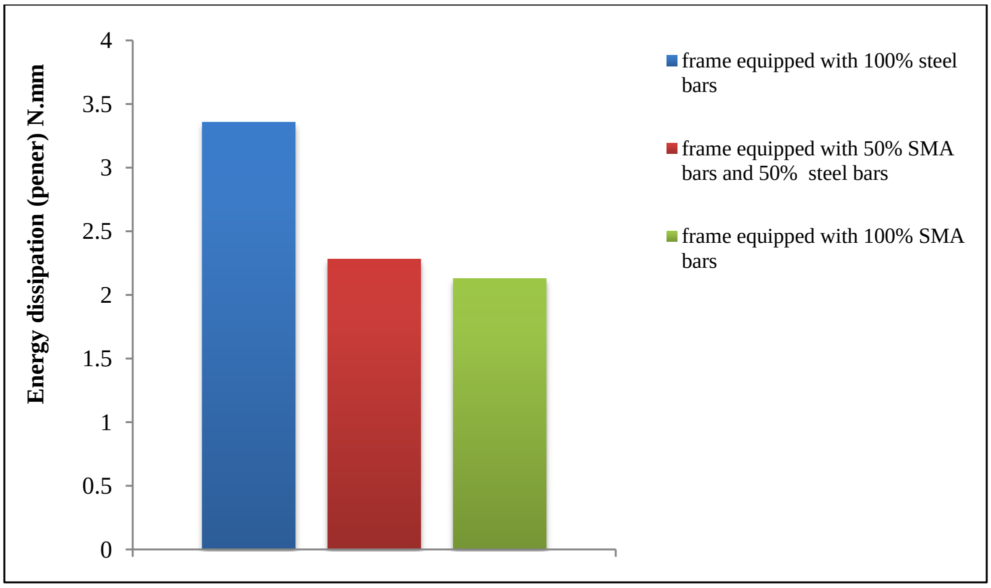


Figure 11. Energy dissipation of frame under time history analysis

4.2.4. Maximum Stress in Building

When added superelastic SMA bars instead of steel bars, it was found that the maximum stress in reference model is larger by (32.5%, 25.4%) as compared with steel building equipped with 100% SMA bars and steel building equipped with 50% SMA bars and 50% HS steel bars respectively, As shown in Figure 12. also adding superelastic SMA bars in a building instead of HS steel bars had a significant influence on the residual stress in the building. Furthermore, the residual stress in reference is taken as 680.24 MPa. While the residual stress in steel building equipped with 100% superelastic SMA bars and steel building equipped with 50% superelastic SMA bars and 50% HS steel bars is taken as (477.54, 481.73) MPa, respectively.

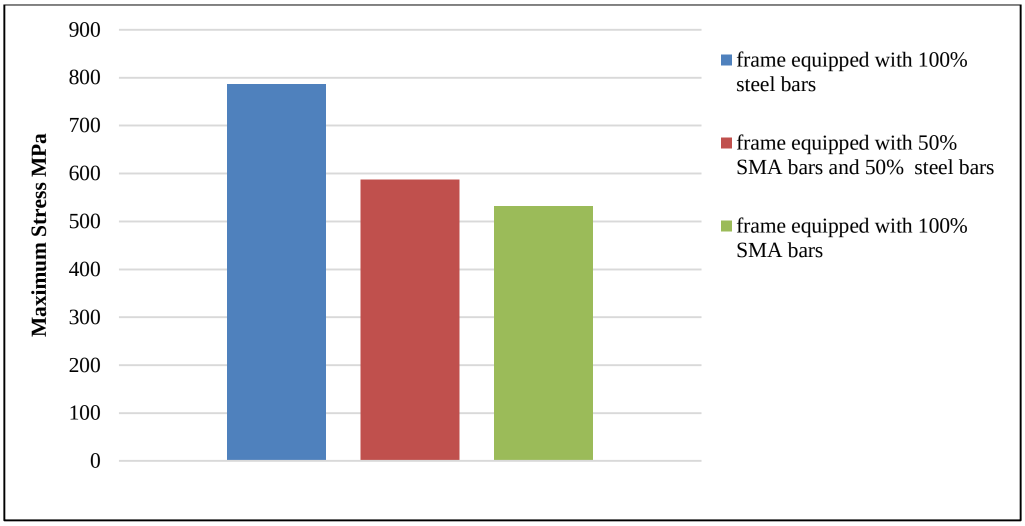


Figure 12. Maximum von Mises stress of the models with a connection having different materials (time history analysis)

5. Conclusion

This paper presents a numerical study on I-shaped beam to HSS column connections integrated with SMAs bars. Based on the numerical findings, the following conclusion can be drawn.

- Introducing superelastic SMA bars at beam-column connection shows excellent recentering ability Due to its superelasticity property. Which the building equipped with 50% SMA bars and 50% HS steel bars could closely fully recenter and the building returns back to its original position with negligible residual inter-story drift at end of time compared to those reference model (building equipped with 100% HS steel bars). While in the case of building equipped with 100% SMA bars the shows high recentering ability and no damping capacity which transfers the building to the opposite side.
- Introducing superelastic SMA bars in the beam-column connection displays better response in the recovery of displacement when compared to the frame equipped with 100% HS steel bars. But several factors would take to be considered, including the methodology used for the connection and cost of the materials.
- Because of large the hysteretic loop of stress-strain of structural steel compared to flag shaped hysteresis of the SMA materials, the building equipped with 50% SMA bars and 50% HS steel bars and 100% SMA bars showed a lower amount of energy dissipation when compared to that of building equipped with 100% HS steel bars.
- Also adding SMA bars in steel building instead of HS steel bars make good advantage towards decreasing stress and residual stress in the building. These extraordinary properties of NiTi SMA beam-column connection could have a great advantage in highly seismic zones, where such a beam-column connection would remain practical even after the strong earthquake.
- In general, the replacement ratio 50% of HS steel bars with superelastic SMA bars provides better seismic performance.

Further research is required in order to examine the size diameter effect of SMA bars and the effect of change the location of SMAs bars and HS steel bars level with beam flange. and further research is also needed to studying another type of alloys

6. Conflicts of Interest

The authors declare no conflict of interest.

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